

Future Mission Trends and Their Implications for the Deep Space Network

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Planning for the upgrade and/or replacement of Deep Space Network (DSN) assets that typically operate for forty or more years necessitates understanding potential customer needs as far into the future as possible. This paper describes the methodology Deep Space Network (DSN) planners use to develop this understanding, some key future mission trends that have emerged from application of this methodology, and the implications of the trends for the DSN's future evolution. For NASA's current plans out to 2030, these trends suggest the need to accommodate: three times as many communication links, downlink rates two orders of magnitude greater than today's, uplink rates some four orders of magnitude greater, and end-to-end link difficulties two-to-three orders of magnitude greater. To meet these challenges, both DSN capacity and capability will need to increase.

I. Introduction: The Mission-Driven Evolution of the Deep Space Network

SINCE its inception, the Deep Space Network has had to evolve its capability and capacity in anticipation of the increasingly challenging missions needing it for communication and navigation support. The Network began under U.S. Army auspices in 1958 with the Jet Propulsion Laboratory's (JPL's) efforts to develop and operate the nation's first satellite, Explorer 1. To receive telemetry and plot the orbit of this satellite, JPL developed the "Microlock" tracking and data acquisition system – a set of somewhat portable tracking stations located at each of four sites: Cape Canaveral, Nigeria, Singapore, and San Diego.¹ Meanwhile, the Department of Defense established the Advanced Research Projects Agency (ARPA) to "promote, coordinate, and manage all existing military and civilian space activities." As part of this responsibility, ARPA was directed to oversee a lunar space program called Pioneer. Understanding that the existing "Microlock" system was inadequate for tracking spacecraft at lunar distances, ARPA approved a JPL plan to adapt an existing 26m radio astronomy antenna design to the tracking of the Pioneer probes at L-band. Three of these antennas were to be procured to form what ARPA referred to as the Tracking and Communications Extraterrestrial Network (TRACE). However, as JPL began construction on the first 26m antenna, the civilian space program was transferred to the newly formed National Aeronautics and Space Administration, and JPL's transfer from the Army to NASA quickly followed. Under this new organizational arrangement, JPL completed the first 26m antenna at the end of 1958 -- located at Fort Irwin in Goldstone, California. The antenna was named Pioneer Station after the first two spacecraft with which it communicated, Pioneers 3 and 4. As NASA pursued increasingly ambitious robotic reconnaissance of the moon, construction of other stations followed. In 1960, JPL supervised the construction of NASA's first overseas station in Woomera, Australia. NASA's second and third overseas stations were constructed near Johannesburg, South Africa (1961) and about 40 miles west of Madrid, Spain (1963). The overseas stations, in conjunction with Goldstone, assured that a station would always be in view of the spacecraft despite the Earth's rotation. On December 24, 1963, JPL's Director, William Pickering, sent out a memo formally designating this growing collection of tracking stations and associated technology endeavors as the "Deep Space Network."

At the time Pickering sent out his memo, NASA was already sending missions to explore the depths of space beyond the moon and had plans to reconnoiter Earth's nearest planetary neighbors – Venus and Mars. The significantly greater range distances associated with these planned destinations prompted expansion of the DSN's capabilities and capacity. More antennas were constructed, some with substantially lower system noise temperatures, higher frequency S-band capability, and 64-meter diameters – improvements all targeted at increasing the received signal power from distant spacecraft.² By the time these improvements were complete, lunar

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exploration had progressed from initial robotic reconnaissance to initial human reconnaissance, making the 64m antennas not only useful for receiving very distant signals but also for receiving the higher data rate signals associated with video being transmitted by astronauts at the moon. Later, NASA's plans for reconnaissance missions to even more distant locations such as Mercury, Jupiter, Saturn, and eventually Uranus and Neptune, drove the DSN to pursue even lower system noise temperatures, higher frequency X-band capability, conversion of its 26-meter and 64-meter antennas to larger 34-meter and 70-meter antennas, and arraying of these antennas (sometimes along with those of radio astronomy facilities) to achieve significantly larger effective receiving areas. DSN-sponsored technology efforts in forward-error correction coding and data compression, coupled with flight project use of more powerful transmitters and larger antennas on the spacecraft, further improved end-to-end link performance during this era.³ With much of the initial reconnaissance of the solar system then complete, NASA began to focus its efforts on more detailed remote sensing and in situ exploration of the solar system, as well as more detailed solar and astrophysical observation.⁴ To facilitate the larger number of spacecraft, greater data return, and greater mission complexity associated with this new focus, the DSN, over the past decade or so, undertook a number of ground- and flight-side improvements. These improvements included constructing additional 34m antennas, testing higher frequency Ka-band downlink capabilities, developing even more efficient forward-error correction codes and data compression algorithms (driven to a great extent by the failure of the Galileo spacecraft's high-gain antenna), and introducing new networking standards and protocols to enable better relay capability between in situ elements, orbital relays, and Earth-based ground systems (both DSN and non-DSN). Figure 1 summarizes the DSN's improvement history relative to the ongoing missions of the time – starting with Explorer 1 and ending with last year's launch of the Mars Reconnaissance Orbiter.

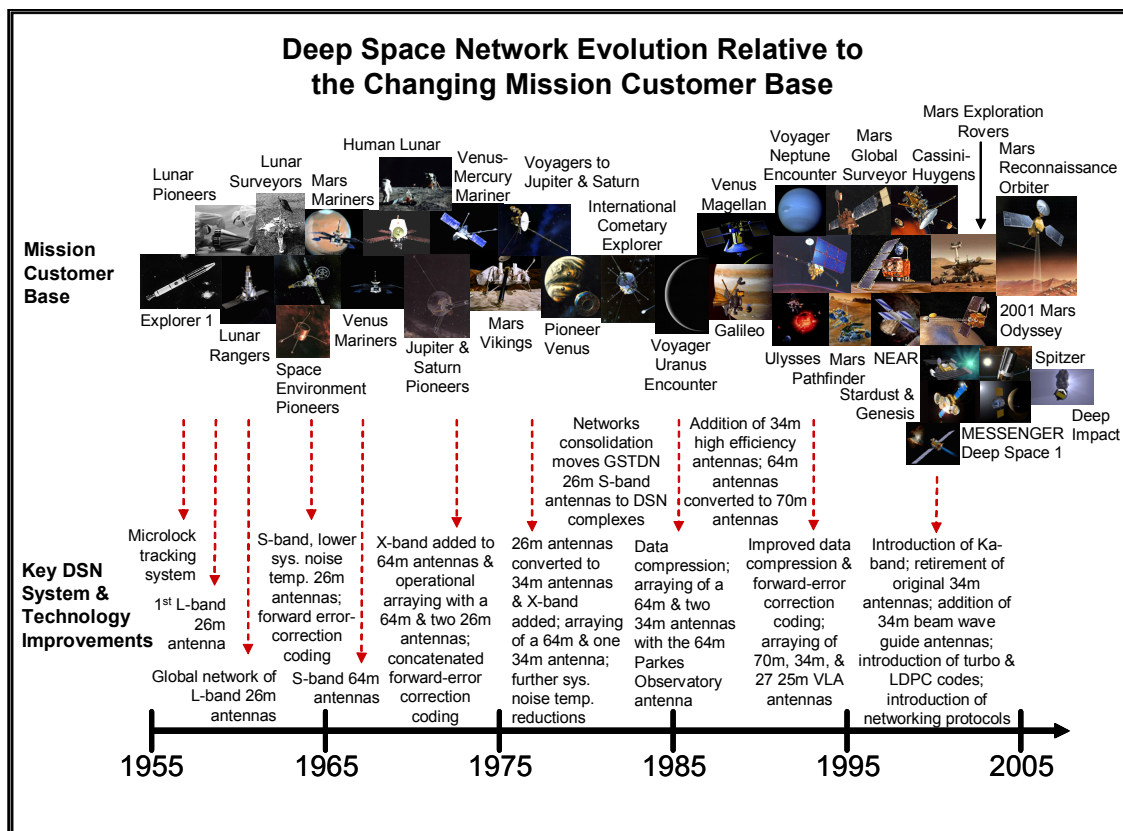


Figure 1. Timeline of key DSN system & technology improvements relative to the evolving mission set.

Today, the DSN consists of 16 large antennas spread across three major complexes: two being the original Goldstone and Madrid sites and the third now being near Canberra, Australia. Each complex hosts one S-band 26-meter antenna and one S- and X-capable 70-meter antenna. The complexes also host different numbers of operational 34-meter antennas. Canberra hosts one S-, X-, and Ka-capable antenna and one S- and X-capable

antenna. Madrid hosts two S- and X-capable 34-meter antennas and one X- and Ka- capable antenna. And, Goldstone hosts two S- and X-capable 34-meter antennas, one X- and Ka-capable antenna, and one S-, X-, and Ka-capable antenna. In addition, Goldstone hosts a high-slew-rate, S-band 34-meter antenna that it inherited from the Army. It has performance somewhat similar to that of a 26-meter antenna. Together, these 16 antennas provide S-, X-, and Ka-band communication and navigation support to ~33 spacecraft operating in various regions of the solar system and beyond.

Some of these 16 antennas, however, originated more than 40 years ago and will likely need refurbishment and/or replacement in the not too distant future. As a recent General Accountability Office (GAO) report noted, the “DSN faces a deteriorating infrastructure and a limited capacity to serve additional missions.”⁵ Such assessments add new urgency to answering a question that the DSN has had to repeatedly grapple with since its inception: what capacity and capability will future missions need? The remainder of this paper describes: the methodology that the DSN’s long-range planners have been using to address this question, some of the key future mission trends that have emerged from the application of this methodology, and the implications of these trends for how the DSN needs to evolve.

II. Methodology for Assessing Future Mission Needs

The methodology for developing an understanding of the DSN’s future mission customer needs entails a four-step process. This process begins with the development of a candidate mission set as a function of time using the latest NASA strategic plans, roadmaps, and official mission set lists. Where other NASA mission modeling efforts exist, the DSN’s planners endeavor to coordinate with such efforts, refining the candidate mission set as necessary to ensure emergence of, and consistency with, a commonly agreed upon “snapshot” of potential mission customers over the time frame of interest. During the past year, NASA Headquarters has attempted to formalize this coordination effort through establishment of a Space Communications Architecture Working Group (SCAWG) that, among many other things, maintains an inter-center Integrated Mission Set (IMS). This author has been an active participant in the development and maintenance of the SCAWG IMS. Several factors have complicated this development and maintenance, including: the release of new Space Science Advisory Committee and human lunar and Mars exploration roadmaps during the first three quarters of FY’05, the disbanding of all such NASA advisory committees in the fourth quarter of FY’05, the budget-related cancellation of several key missions (e.g., Jupiter Icy Moons Orbiter, Mars Telecommunications Orbiter, etc.) in the first quarter of FY’06, the NASA Program Analysis & Evaluation (PA&E) Office’s introduction of a new Agency Mission Planning Model (AMPM) in the same time period, a subsequent limited release of Constellation program requirements, and, in the second quarter of FY’06, the release of NASA’s FY’07 Budget Request. The last available SCAWG IMS baseline, dated December 14, 2005, accounts for all of these perturbations except for the limited release of Constellation program requirements and NASA’s FY’07 Budget Request. The analysis described in this paper is based on a mission set consistent with the baseline SCAWG IMS, except that it includes adjustments for the Constellation requirements and mission deferrals implied by NASA’s FY’07 Budget Request. Note that, in May 2006, after the analysis was conducted, PA&E released a new Agency Mission Planning Model. Where this new model may have a bearing on the analysis results, it is noted in the paper.

In the second step of the process, the DSN’s planners work to derive the telecommunications-pertinent parameters for each of the missions identified in the first step. To do this they research mission requirements documents, sift through review presentations, scrutinize concept studies, and whenever possible, confer with actual flight project or study team personnel. The associated research effort can take a matter of months and is probably the most daunting part of the whole future mission needs assessment process.

The third step involves analyzing these parameters as a function of time (generally at 5-year intervals) to provide an indication of the evolving customer needs out to the time horizon of interest. The results of these analyses are usually displayed as bar graphs and scatter plots with curve fits to show the general trend lines. Trends of interest to the DSN’s planners typically include (but are not limited to) number of potential mission-, spacecraft-, and link-supports, downlink and uplink data rates, and end-to-end link difficulty (expressed in terms of data rate times distance squared). In addition, by applying communications link budget analysis to much of the source data gathered during the second step, the DSN’s planners can transform aggregate mission requirements into specific DSN requirements for things like gain over system noise temperature, effective isotropic radiated power, and, for specific architectural assumptions, even the number of antennas of a given diameter needed as a function of time.

The fourth and final step of the future mission needs assessment process involves performing a sensitivity analysis and/or some type of “sanity check” on the trend results. A variety of factors can cause future mission needs to be either over- or underestimated. Overestimates typically arise during the mission set identification step.

Sometimes, for instance, NASA roadmaps may prove optimistic in their mission and spacecraft expectations – with budgetary pressures subsequently reducing these expectations. To the extent that the trend analysis mission set has been heavily derived from such roadmaps, it may inadvertently overestimate future mission requirements. One way to guard against such overestimates is to conduct a Monte Carlo or quasi-Monte Carlo sensitivity analysis that looks at how much variation in anticipated trends occurs as randomly selected missions are removed from the mission set on each of many separate runs.⁶ Trends that endure across all the separate runs can be considered relatively impervious to budget-induced fluctuations in the future mission set. However, in the absence of appropriate Monte Carlo simulation software (which this author is currently working to develop), the conduct of such an analysis can be rather tedious and time-consuming. A simpler, quicker, albeit less precise, approach is to give some thought to the types of missions that might be driving a particular trend, then ascertain the number of such missions relative to the total number of missions in the mission set. If only one or two missions turn out to be drivers in an otherwise large mission set, the trend may be hard to “bank on” unless the driver missions have exceedingly strong political backing.

Underestimates typically arise during the derivation of telecom-pertinent parameters for each of the missions in the mission set. Because mission and spacecraft designers do not have a reliable means for knowing the capabilities that may exist in, say, 2025 or 2030, the telecom-pertinent parameters appearing in mission studies for such time frames are susceptible to bias toward today’s capabilities and, hence, may lead to trends that underestimate what will actually be required. To assess such potential for bias, the DSN’s planners try to identify Earth-based science capability trends that can be used as benchmarks relative to deep space science capability needs. For instance, in the data rate realm, today’s remote sensing capabilities at Earth suggest what data rates will ultimately be needed to support high-fidelity remote sensing observations at another planet.⁷ With such benchmarks in hand, planners have a better feel for whether the derived trends are likely to be underestimates or not. However, this technique is difficult to apply if the trend in question pertains to asset loading. Because demand tends to rise in response to available capacity and capability (assuming no pricing policies are in place to discourage this), planners may find that the actual loading for a new class of asset, once implemented, exceeds what was projected. The situation is somewhat analogous to adding an extra lane on a freeway. The easier driving conditions associated with the extra lane attract more drivers, leading, in some cases, to more crowding than there was originally. Fortunately, from the DSN planner’s perspective, this source of trend underestimation is frequently offset by the source of trend overestimation previously discussed. In effect, the budget limitations that drive down the size of the anticipated mission set serve as the “pricing policies” that limit the extent to which mission set demand rises in response to available capacity and capability.

A final “sanity check” for guarding against trend over- and underestimates is to look at how well the projected trends agree with historical trends. Except in the cases of national crises or the introduction of revolutionary technologies, mission needs can be expected to change gradually. Hence, any significant, unexplained discontinuities between historical and projected trends constitute grounds for suspecting problems with the trend estimates.

The remainder of this paper describes some of the key future mission trends that have emerged from the application of this four-step methodology and the implications of these trends for how the DSN needs to evolve.

III. Results from the Future Mission Needs Assessment

Results from the future mission needs assessment encompass four types of trend parameters: number of potential mission-, spacecraft-, and link-supports, maximum downlink data rates, maximum uplink data rates, and end-to-end link difficulty. For each class of parameter, sensitivity analysis considerations and historical “sanity checks” are also discussed.

A. Anticipated Number of Mission, Spacecraft, and Link Supports

Figure 2 shows the total number of downlinks, spacecraft, and missions anticipated as a function of time. On average, the number of missions does not grow much over the next two-and-a-half decades. This observation is consistent with the expectation in the President’s *Vision for Space Exploration* that NASA’s budget will not grow at a rate much greater than inflation beyond 2009.⁸ Note, however, that the number of spacecraft downlinks roughly triples over the same time period.

This disparity between mission and spacecraft downlink numbers is attributable to a couple of factors. First, and foremost, future mission plans increasingly entail the use of multiple spacecraft. In the case of solar and astrophysical observatories, for instance, achieving higher-fidelity observations necessitates putting larger effective telescope apertures and longer interferometric baselines into space. Since launch vehicle payload fairings tend to

constrain the size of telescope and interferometer that can be carried on the rocket, scientists and mission planners are increasingly turning to the use of multiple spacecraft (and associated launches) to synthesize, on orbit, larger effective telescope apertures and longer interferometric baselines. Multiple spacecraft are also viewed as useful to missions trying to sample phenomena distributed over large spatial regions – such as the Earth’s magnetotail. In the case of in situ exploration, as missions move from short-lived probes to much longer-lived, mobile exploration, they tend to involve more elements (rovers, landers, and orbiters) that have to communicate with one another and the Earth. And, in the case of human exploration, plans call for multiple mission elements such as crew exploration vehicles, lunar surface ascent modules, and various other types of support vehicles that must all have the capability to communicate directly with the Earth.

A second factor contributing to the disparity between mission and spacecraft downlink numbers is the fact that some spacecraft utilize two downlinks: one for engineering telemetry and one for science data return. And, in the human exploration realm, multiple downlinks from each type of exploration vehicle are planned as well. This is why, in Fig. 2, there is also a disparity between the number of spacecraft downlinks and the number of spacecraft. The fact that there are multiple, contributing factors from multiple mission types shaping the observed trend suggests that it is likely to endure despite perturbations in the future mission set.

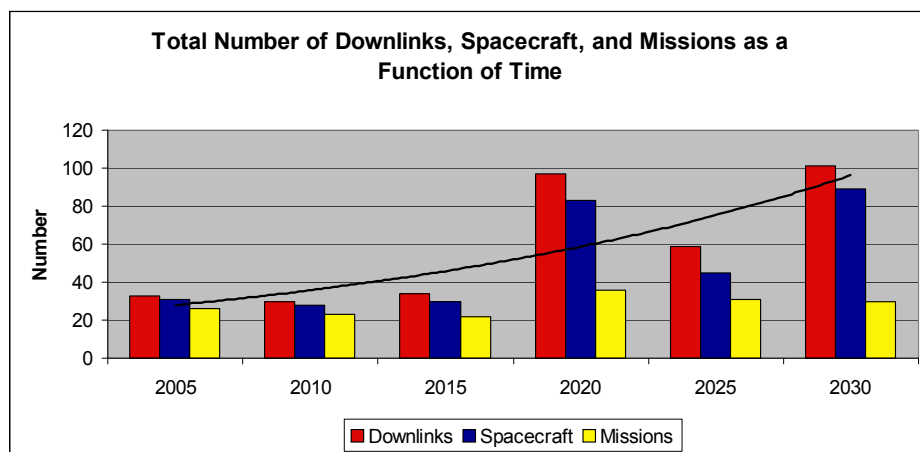


Figure 2. Anticipated number of DSN-supported missions, spacecraft, and links: 2005-2030

One such perturbation has already occurred. In the latest Agency Mission Planning Model, MagCon, a constellation of ~34 spacecraft that was driving the number of downlinks in 2020, no longer appears. Hence, a plot reflecting this revised data point would be much more consistent with the 2020 level indicated by the trend line.

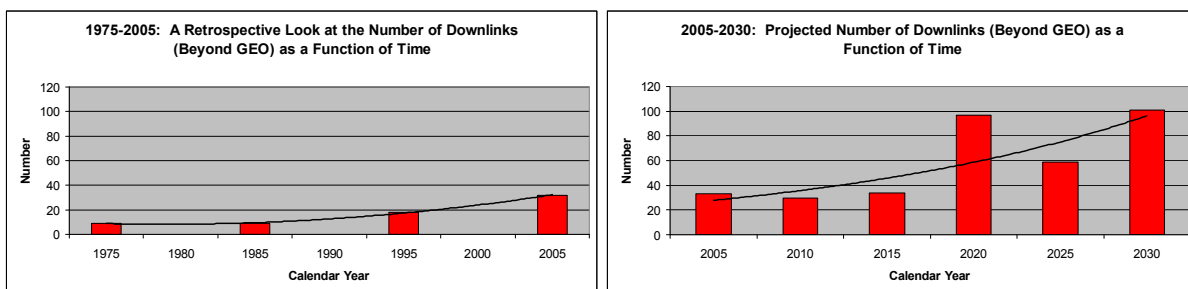


Figure 3. Performing a “sanity check”: A side-by-side comparison of historical and projected link number trends.

Figure 3 provides an historical “sanity check” on our projected downlink trend. Both the projected and historical trend lines are of similar form and slope – no major discontinuities. And, over similar time intervals, both the

historical and projected number of links more than triple. Somewhat different mechanisms are at work, since much of the downlink increase during the past 30 years is attributable to an increase in the number of supported missions, while the projected increase over the next 25 years is due to an increase in the number of spacecraft and associated links per mission. Nonetheless, the projected trend appears to be “in the ball park” relative to the historical one.

B. Anticipated Maximum Downlink Rates

Figure 4 shows the maximum downlink data rates anticipated as a function of time along with some of the key mission drivers at each 5-year time slice. The associated trend line increases between 1 and 2 orders of magnitude over the next 25 years. At least two classes of missions appear to drive the bulk of the trend: high data rate observatory-class missions and human-focused lunar and Mars exploration missions. Note that neither Lunar Orbiter #2 nor any of the lunar relay missions appear in the recent May 2006 Agency Mission Planning Model. Deletion of these missions, however, would not significantly change the trend line.

Another item to note is that a number of the data points from 2010 to 2030 appear to be hovering around 100 to 150 Mbps. This may be indicative of a perceived, spectrum-allocation-related data rate “ceiling” on the part of NASA’s spacecraft and mission designers. At Ka-band, there are 1,500 MHz of bandwidth available at around 26 GHz and 500 MHz of bandwidth available at around 32 GHz – with the bandwidth being much larger than what is available in the lower-frequency S- and X-band allocations. However, a single spacecraft downlinking at 150 Mbps, assuming bandwidth-efficient QPSK modulation and a rate one-half forward-error correction code, would, at 26 GHz, use up 20% of the available bandwidth and, at 32 GHz, use up 60%. To the extent that more than one spacecraft in the same part of the sky might want to use Ka-band, these percentages start to look quite significant – i.e., available bandwidth begins to look like a potential constraint on future downlink data rates. Fortunately, there may be ways around this constraint including: securing additional Ka-band spectrum, switching to even more bandwidth-efficient modulation schemes, and/or developing more efficient forward-error correction codes (to the extent allowable within Shannon’s limit). Hence, it is possible that the trend shown here may underestimate the downlink rates we will be seeing within a couple of decades.

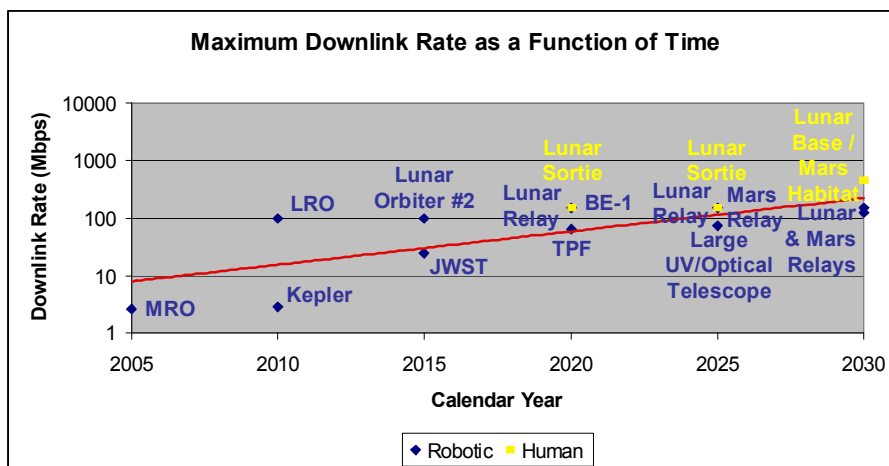


Figure 4. Anticipated maximum downlink data rates: 2005-2030.

Figure 5 provides another historical “sanity check,” this time on our projected trend for downlink data rate. Comparing Fig. 4 and 5, we see that both the projected and historical trend lines are of similar form. The historical trend line in Fig. 5 has a slightly steeper slope – more than two orders-of-magnitude increase as opposed to the one-and-a-half, or so, associated with the projected trend line. Nonetheless, the projected trend once again appears to be “in the ball park” relative to the historical one.

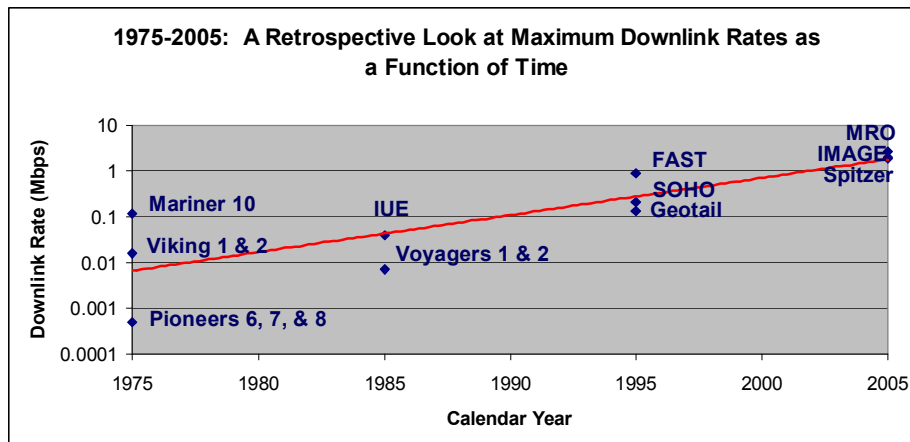


Figure 5. A “sanity check” on projected downlink data rates: the historical trend from 1975 to 2005.

C. Anticipated Maximum Uplink Rates

Figure 6 shows the maximum uplink rates anticipated as a function of time. Two trend lines are shown for these rates: one for robotic missions and one for human exploration missions. The reason for this dichotomy between robotic and human uplink trends has to do with the inherent nature of human-to-human communications. Such communications tend to involve more symmetric information exchanges between the sender and receiver. Hence, human missions exhibit uplink and downlink data rates that are far more symmetric than those for robotic missions.

Human rates are projected to increase between one and two orders-of-magnitude between 2015 and 2030. By 2030, such rates are expected to be four orders-of-magnitude greater than the robotic rates the DSN supports today. To the extent that human missions will drive a need for robotic relay capability in support of lunar and Mars surface missions, these robotic uplink rates will also increase roughly three orders-of-magnitude by 2030.

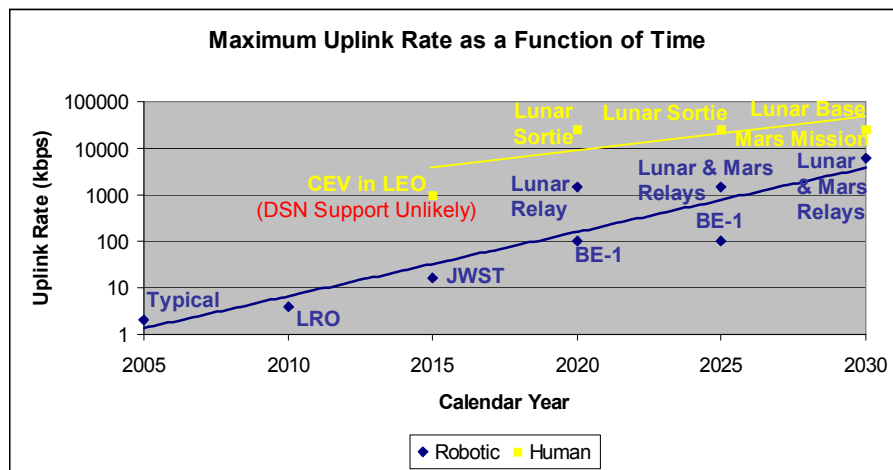


Figure 6. Anticipated maximum uplink rates: 2005-2030.

Without such human-mission-related relays, however, robotic uplink rates can still be expected to climb some two orders-of-magnitude over today’s rates. This increase in robotic uplink rates appears to be associated with a change in the nature of what dominates uplink communications. In the past, such communications have been dominated by the transmission of low-level spacecraft commands. Historically, such commands have not required uplink rates in excess of 2 kbps – hence, uplink rates have changed very little over the past couple of decades. More

recently, however, missions have begun infusing new technologies that demand large data and software information uploads, making past history in this case a poor indicator of future mission requirements. The upcoming James Webb Space Telescope (JWST), for instance, has been baselining a 16 kbps uplink rate to support the upload of its instrument calibration flats.⁹ Future observatories are baselining even higher uplink rates. Meanwhile, concepts for long-lived rovers and aero-rovers are incorporating greater onboard autonomy to facilitate negotiating obstacles in real time rather than awaiting long-light-time commands from Earth.¹⁰ This greater onboard autonomy, however, necessitates periodic software updates and large image or terrain files to support in situ navigation. One can see why such updates might drive uplink rates by looking at how long it took for the Mars Exploration Rovers (MER) to achieve an 8.2 MB flight software upload while en route to Mars (Fig. 7). To the extent that more complex software for enabling rover autonomy might involve uploads closer in size to something like Windows XP, Fig. 7 further highlights the consequences of remaining at today's uplink rates. Examination of terrestrial analogs such as in-flight retargetable cruise missiles, unmanned aerial vehicles, and unmanned ground vehicles suggest future mission uplink rates on the order of 200 kbps¹¹ -- a level consistent with the two order-of-magnitude increase in robotic uplink rates that Fig. 6 indicates would occur in the absence of any human-mission-related relay drivers.

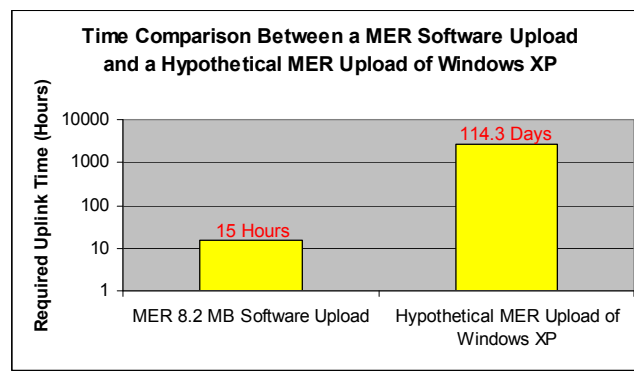


Figure 7. Uplink rate constraints inherent in actual and hypothetical flight software upload times.

D. Anticipated Maximum End-to-End Link Difficulty

The difficulty of establishing a link between a spacecraft and a DSN station is, to a first order, a function of the required data rate and the square of the distance over which the link is occurring. Hence, a simple measure of end-to-end link difficulty can be obtained by taking the product of the data rate and the square of the distance. Note that this measure makes no assumptions about the telecommunications capabilities of either the spacecraft or the DSN ground station at each end of the link. It is simply indicative of the inherent difficulty of the link itself.

Figure 8 shows the maximum anticipated end-to-end downlink difficulty as a function of time. Over the next 25 years, this downlink difficulty increases roughly two-and-a-half orders-of-magnitude. In the 2005 and 2010 time frames, extreme distance missions tend to drive the trend. However, in 2015 and beyond, high data rate missions become at least as important a factor. Note that the trend driver missions include a significant number of robotic Mars, robotic outer planet, and human Mars missions. This mission diversity suggests trend robustness, despite the inevitable perturbations in the future mission set. And, it is consistent with the change in the space exploration paradigm discussed in the introduction -- a change from planetary reconnaissance to much more detailed orbital remote sensing and in situ exploration. This greater detail generates larger data volumes which require higher data rates to return. At planetary distances, these higher data rates result in more challenging end-to-end links.

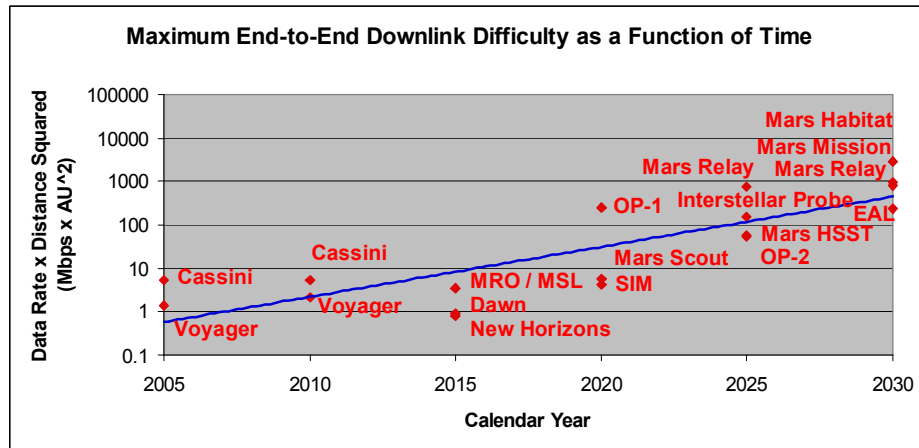


Figure 8. Anticipated maximum end-to-end downlink difficulty: 2005-2030.

Figure 9 provides an historical “sanity check” on the projected downlink difficulty trend. Comparing Fig. 8 and Fig. 9, we see that both the projected and historical trend lines are of similar form. The historical trend line in Fig. 9 has a slightly shallower slope – less than two orders-of-magnitude increase as opposed to the two-and-a-half, or so, associated with the projected trend line. This slight discrepancy in change magnitude between the historical and projected trends may be attributable to the changing nature of the space exploration paradigm as discussed above. The historical trend covers an era characterized by preliminary reconnaissance. The increasing link difficulties are all driven primarily by distance. To compensate for these increasingly challenging links, two things occurred: (1) the DSN made a number of improvements designed to increase the effective receiving area of its antennas (see introduction) and (2), at distances where the improvements no longer fully compensated, the key driver spacecraft (e.g., the Voyagers) dropped their data rates – effectively lowering the magnitude of the link difficulty trend. The projected trend, on the other hand, covers an era characterized, from 2015 onward, by detailed orbital remote sensing and in situ exploration. The key driver spacecraft in this time frame operate at planetary distances with data rates that cannot readily be dropped given the larger data volumes that need to be returned – hence, the slightly steeper slope. In any event, the projected trend appears, once again, to be “in the ball park” relative to the historical trend.

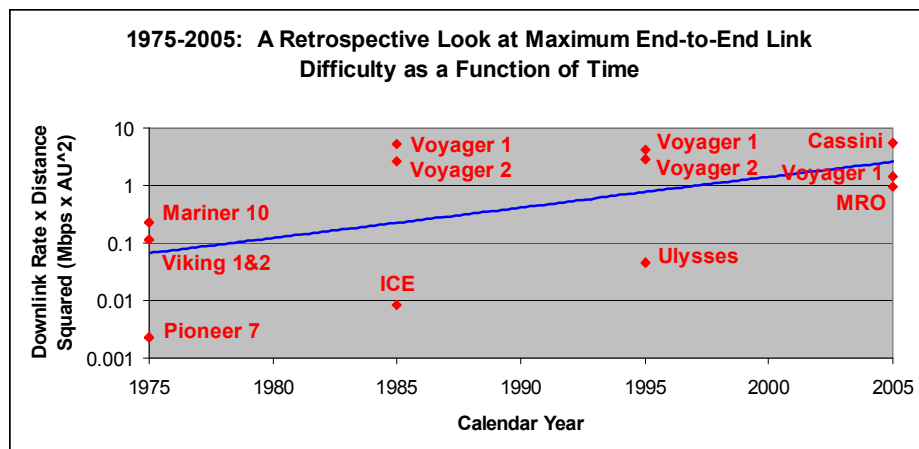


Figure 9. A “sanity check” on projected downlink difficulty: the historical trend from 1975 to 2005.

End-to-end uplink difficulty trends are, of course, similar to those of the downlink difficulty trends and involve roughly the same driver missions. However, because of the asymmetry between uplink and downlink rates for robotic missions discussed earlier, the effective isotropic radiated power needed to support the uplink to such missions is within the capability of the current DSN (assuming appropriately sized high-gain antennas onboard the spacecraft and forward-error correction coding on the uplink when needed). Only human Mars missions in the 2030 timeframe, with uplink rates in the tens of megabits per second, pose end-to-end uplink difficulties that exceed today's routine uplink capabilities. However, such requirements and their associated link difficulties are generally bounded by the problem of providing emergency uplink at outer planet distances. The DSN's current 70-meter, 20 kW, X-band capability enables spacecraft out to about Jupiter's maximum distance from the Earth to receive a 7.8125 bps emergency transmission via their omni-antennas.¹² To enable emergency uplink into an omni antenna at greater distances, the equivalent of 10 to 20 times the current 20 kW capability on a 70m is needed, depending upon one's spacecraft assumptions (e.g., system temperature, receiver loop bandwidth, etc.). Of course, such distant spacecraft are generally Earth-pointed when they are in a sun-pointed safe mode and, hence, may be able to rely on medium gain antennas – an approach that the New Horizons mission to Pluto has adopted in order to work within the current 70m capability. Nonetheless, one can imagine situations where this approach might not work including spacecraft failures that compromise attitude control and landers on outer planet moons with unpredictable antenna pointing attitudes. Such situations suggest that emergency uplink will remain an enduring challenge -- likely to encompass that posed by routine uplink.

IV. Conclusion: Implications for the Deep Space Network

Over the past 48 years, the Deep Space Network and its antecedents have had to grow in terms of both capacity and capability to meet the needs of a continuously evolving and increasingly challenging mission set. Results from the latest future mission needs assessment suggest that the next 25 years will demand continued capacity and capability growth, largely as a result of the transition occurring in space exploration – a transition from preliminary reconnaissance and surveys to more sustained, higher fidelity observation.

In the capacity realm, the DSN will likely need to support three times as many communication links in 2030 as it does today – not because the number of missions will increase that much, but because observatory-class missions will increasingly rely on multiple spacecraft to synthesize larger telescopes and interferometers and sample phenomena distributed over large spatial regions. In situ exploration, both robotic and human, will also contribute to this requirement through increased reliance on multiple surface elements working in conjunction with each other and with orbiters. Supporting this larger number of links will likely require an increase in the number of antennas available to service the links and expanded use of multiple channels per antenna for instances where closely-spaced spacecraft fall within the beam width of a single antenna. Even with this expanded capacity, the DSN will also likely face increased asset scheduling challenges, suggesting a migration away from manually intensive processes to more automated, protocol-dependent approaches akin to the way messages are routed through the internet – a vision that also embodies a significant flight-side technology component.¹³

In the capability realm, the DSN will likely need to accommodate downlink rates up to two orders-of-magnitude higher than today's and uplink rates up to four orders-of-magnitude higher. The increase in downlink rates is driven primarily by the transition of NASA's solar system exploration from brief flyby reconnaissance missions to more detailed orbital remote sensing missions occurring at higher spatial, spectral, and temporal resolutions. These higher fidelity missions generate larger data volumes which then require higher data rates to downlink in reasonable amounts of time. To accommodate these larger data volumes and higher associated data rates, the DSN will need to ensure that its receivers, telemetry processors, decoders, formatters, data recorder forwarding rates, and communication lines to JPL evolve to be compatible. It will also need to pursue more efficient coding, compression, and modulation schemes to fit these higher data rates into existing spectrum bandwidth allocations – and/or advocate for larger allocations. The increase in uplink rates is primarily driven by the symmetric nature of human-mission communications and the increasing software and data upload requirements of increasingly autonomous robotic in situ explorers. As with accommodation of the higher downlink rates, accommodating these higher uplink rates will necessitate evolving the antenna front- and back-end electronics to be compatible. And, similar to the downlink, these higher rates and their associated bandwidth requirements may necessitate more attention to efficient coding, compression, and modulation on the uplink – again, with possible advocacy for additional spectrum allocation.

Given that the received signal power is inversely proportional to the square of the range distance, higher downlink and uplink rates at the vast distances associated with the other planets also translate into more challenging end-to-end links. As a result, end-to-end downlink difficulty is projected to grow two-to-three orders of magnitude by 2030. Such growth in end-to-end downlink difficulty suggests a need to pursue up to four potential improvement

thrusts. The first improvement thrust involves continuing the historic migration to higher frequency bands – since, to a first order, the received signal power in a link between two high-gain antennas is proportional to the square of the frequency. As noted in the introduction, the latest step in this migration has been the introduction of Ka-band.¹⁴ Optical communications may ultimately follow. A second improvement thrust involves increasing the effective receiving area of the DSN’s antennas -- since the received signal power is also directly proportional to the area of the receiving antenna. In the past, this increase in effective receiving area has been achieved in two ways: by enlarging the antennas themselves and by arraying antennas. Cost trades suggest that arrays of small-to-medium-sized antennas can be built more cheaply than very large, single antennas having the same effective area.¹⁵ Hence, the DSN has been focusing considerable study on the construction of large arrays of antennas.¹⁶ A third improvement thrust involves continuing to advance forward-error-correction-code and data-compression-algorithm efficiencies such that the same amount of information can be received at a lower signal power – thereby reducing the amount of effective receiving area needed. And, a fourth and final improvement thrust involves advancing flight-side antenna, transmitter, and relay radio technologies so that flight projects can transmit their data back to the DSN’s antennas with higher effective isotropic radiated powers – again reducing the amount of effective receiving area needed at Earth. As we saw in the introduction, all of these potential improvement thrusts have been successfully pursued in the past; and, with today’s technology, should be capable of further advancement.

The higher projected end-to-end uplink difficulty requires, to some extent, pursuing the same improvement thrusts identified for addressing end-to-end downlink difficulty, except with the flight and ground locales for these improvements reversed. However, as noted earlier, routine uplink data rate requirements remain low enough such that emergency uplink requirements at outer planet distances tend to be more driving. The emergency nature of the uplink requirement tends to limit what sorts of performance improvements can be expected on the flight side, leading to a focus on enhancing the effective isotropic radiated power available on the ground side. Possibilities for increasing ground-side effective isotropic radiated power include putting higher-power transmitters on existing antennas and/or arraying the uplink from numerous smaller antennas to synthesize both a larger effective transmitting area and a larger effective transmitter power.¹⁷

While all of these DSN capacity and capability growth implications are predicated on telecommunications trends derived from a mission set that will undoubtedly change with time, sensitivity analysis considerations and historical “sanity checks” suggest that the trends themselves are resilient to such changes. The trends tend to be driven by multiple types of missions such that, even when one or more specific mission drivers go away, the overall trends still remain. And, relative to 30-year historical trends for the same telecommunication parameters, most of the future mission trends exhibit reassuringly similar directions and slopes. Thus, barring a national crisis or a revolutionary new technology emerging that totally changes NASA priorities, there is reason to believe that the capacity and capability growth implications cited above are well founded. In working to address these implications, the DSN will continue its rich 48-year history of evolving to enable the next great generation of space exploration missions.

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